Some Aspects of Cadmium Flow in the U.S.

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A team of Purdue University engineers and scientists has been involved in studying sources, transloca-
tion mechanisms, and fate of cadmium in the environment. One of the principal results of this work has
been the development of a cadmium flow model for the U. S. which involves simulating sources, use
patterns, waste treatment and recovery techniques, waste disposal options, and environmental flow
mechanisms. A series of model calculations performed specify cadmium environmental flow, fate, and
human exposure for a variety of use pattern, waste treatment/recovery, and disposal scenarios over a
ten-year simulation period.

The intent of this paper is to report initial results
of a simulation of the flow of Cd in the U. S. envi-
ronment. These results are by no means complete;
there are important elements of the total U. S. Cd
flow pattern which are not accounted for in this
work to date. For example, Cd discharges from lead
and zinc smelters and resultant dispersion through
the environment were not completed as of the time
this paper was prepared.

The present Cd flow calculations cover a ten-year
simulation period and include the following sources
of Cd discharge to the environment: electroplating
facilities, pigment manufacturers, plasticizer pro-
ducers, battery manufacturers, coal fired power
plants, steel producers, sewage treatment plants,
and municipal/commercial incinerators. The quan-
tification of Cd discharges from the foregoing
process/facilities is done by way of compartmental
models of Cd flow within each process, and its re-
lated waste treatment and waste disposal alterna-
tives. For the present calculations, current process
configurations and associated waste treatment and
disposal practices are presumed to apply through-
out the ten year simulation period. The Cd con-
sumption pattern used for the simulation is given in
Table 1. Annual Cd consumption for the ten-year
period is assumed to be 5000 Mt initially (*1*) and to
increase by 280 Mt each year of the simulation
period. The modest ≤ 5% annual increase in Cd
consumption is a reflection of the anticipated im-

Table 1. Cd consumption/utilization assumptions for
10-year simulation period.

Use	Fraction of annual Cd consumption[a]
Electroplating	0.55
Pigments	0.12
Plastics	0.20
Ni-Cd batteries	0.05
Miscellaneous	0.08

[a] Assumed Cd consumption (10^3 Mt/yr); $5.0 + 0.25t$, where t is
time.

pact of present and proposed environmental re-
strictions which are expected to restrain growth in
the Cd market in the foreseeable future.

The array of computer codes and analytical
methods used to characterize Cd flow in the U. S.
as well as the associated exposure analysis is por-
trayed in Figure 1. As indicated previously, Cd re-
lease to the environment by the sources enumerated
above is simulated by way of the compartmental
flow model COMP. This model has provisions for
time dependent sources as well as demand adjusted
and time dependent transfer coefficients. The dis-
persion and subsequent deposition of Cd-bearing
particulate/aerosols from both area and point
sources is calculated with the ATM and AQDM
Gaussean diffusion models (*2, 3*). The movement of
Cd adsorbed to sediment particles by way of stream
flow is treated with the SEDTRN subroutine of the
Wisconsin Hydrologic Transport Model (WHTM)
(*4*). The deposition of Cd-bearing solids on flood-
plains and in reservoirs is simulated by modifica-

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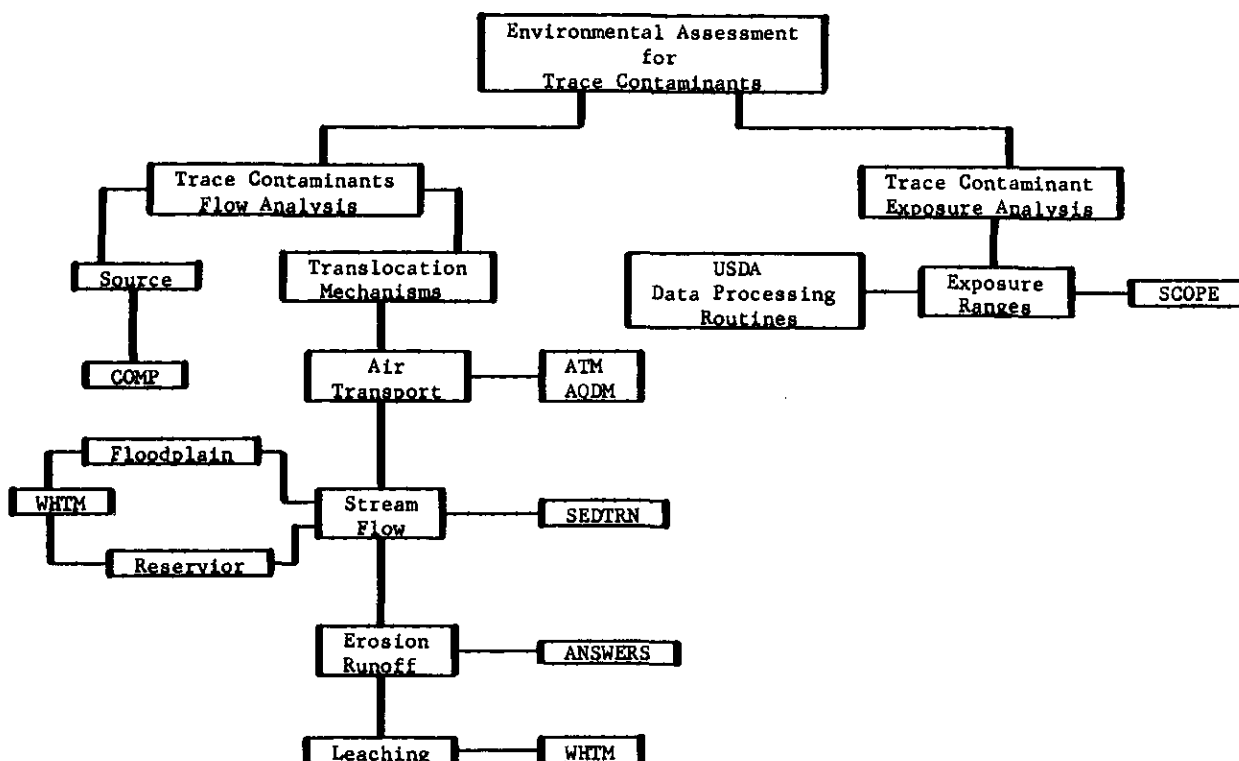ment, Purdue University, West Lafayette, Indiana 47907.

FIGURE 1. Computer codes and analytical methodologies employed in a typical environmental assessment for a trace contaminant.

tions of WHTM subroutines, as is the leaching of Cd from waste disposal sites. The erosion of sludge and/or fertilizer amended soils, with subsequent transport to waterways, is accounted for with AN-SWERS, a model developed at Purdue for the U. S. Environmental Protection Agency (5,6).

A statistical/stochastic approach to the problem of estimating the range of human exposure to trace contaminants has been developed in the form of the computer program SCOPE. Inasmuch as the major route of ingestion of many of the trace contaminants known to be a threat to human health is by way of dietary intake (food and beverage), the 1965-66 USDA dietary intake study data tapes have been made operative on the Purdue University CDC 6500 computer. A number of data processing/analysis routines have been developed for the purpose of generating a variety of "working tapes" from the original set of USDA data. These routines prepare data for input to SCOPE which in turn generates frequency histograms for the dietary intake of trace contaminants for individual food items, or for combinations of foods up to and including the total diet. Thus the array of computer programs and/or analytical techniques available at Purdue for the environmental assessment for trace contaminants are of two types: (a) compartmental flow of trace con-

taminants, and (b) statistical/stochastic methods for determining the range of human exposure to trace contaminants given the flow analysis data generated with codes (a).

The compartmental model computer code COMP was used for the purpose of simulating Cd emission rates associated with primary Cd uses and selected inadvertent sources. Each COMP Cd flow calculation is actually a composite of eleven interrelated module calculations, each of which represents a use/inadvertent source. A discussion of each model and the associated model parameter evaluation follows.

Models and Model Parameter Evaluation

Electroplating

Inasmuch as the electroplating industry represents the single largest consumer of Cd, this module is by design more comprehensive than certain of the others representing substantially smaller uses/inadvertent sources. The Cd module flow schematic is given in Figure 2 as an example of the flow system incorporated into the COMP calculations. The
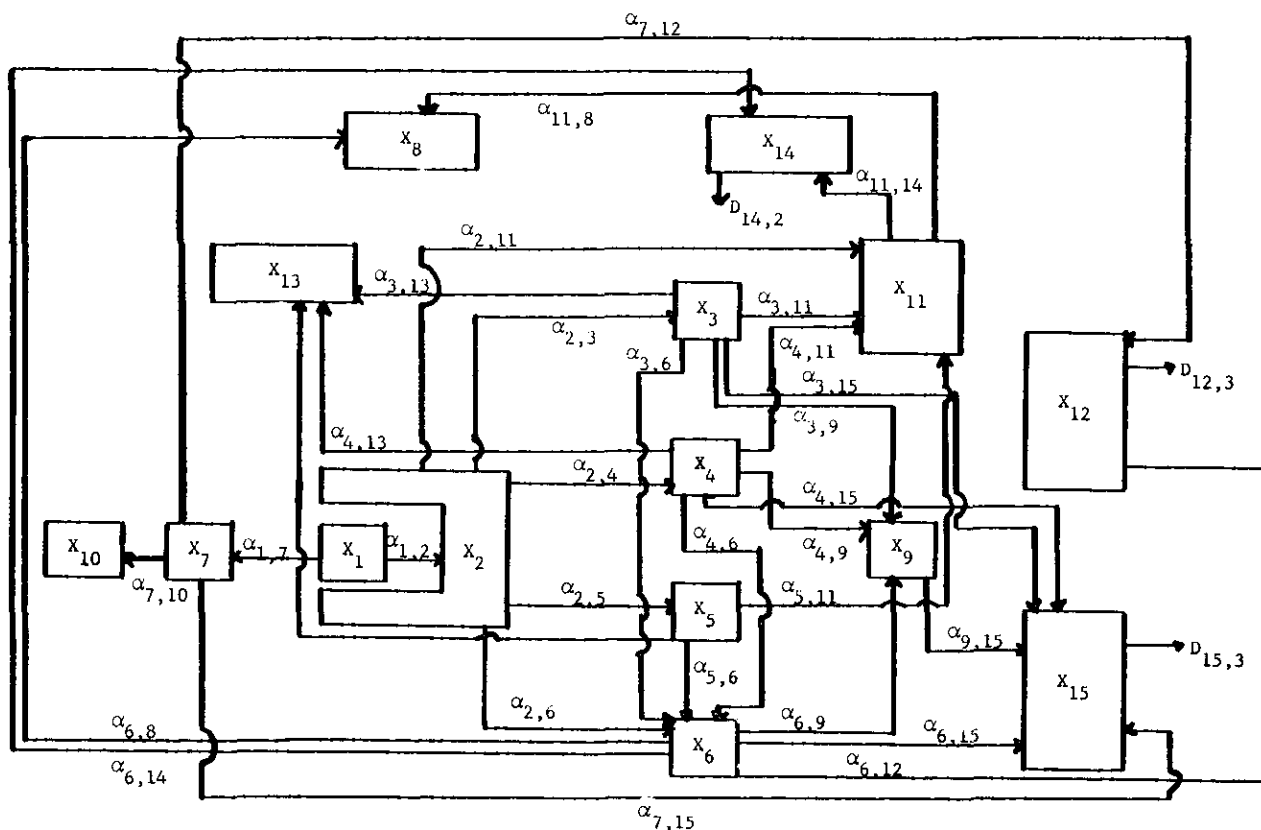
Figure 2. Cd electroplating waste treatment/recovery and product disposal flow model.

module embodies waste treatment and recovery techniques which are presently being marketed and used to a significant extent. Definitions of model components are given below: X_1, Cd metal utilized for electroplating; X_2, Cd production losses; X_3, ion exchange recovery; X_4, reverse osmosis recovery; X_5, evaporative recovery; X_6, chemical destruct waste treatment; X_7, Cd on plated products; X_8, sewage treatment plant; X_9, waste scavenger; X_{10}, steel scrap recycle; X_{11}, no treatment; X_{12}, land dumping (unlicensed sites); X_{13}, Cd recycle; X_{14}, natural waters; X_{15}, landfill (licensed, authorized sites).

Values of the transfer coefficients (α) were derived from data and insight of the Purdue group long associated with research and performance testing in the electroplating waste treatment area, together with studies performed by other groups (7–23). In some cases, coefficient values represent educated guesses rather than well defined estimates inasmuch as data are not available for more precise definition. This is particularly true in estimates of industry-wide practice in the electroplating waste treatment and recovery area.

Of the Cd purchased for electroplating/metal finishing purposes, 10% is typically lost to the plating process in the form of plating solutions carried over into running rinses, spills, etching of plated metal in acid baths/bright dips, spent solution dumps metered to plant waste water stream, etc. (7, 8). The balance of the purchased metal, 90%, is thus sent out on the work produced by platers. Of Cd plating lines, 2% employ ion exchange recovery on post-plating rinses over the simulation period, and another 2% employ in similar fashion reverse osmosis techniques. These relatively small use factors reflect the fact that the great majority of Cd plating is done with cyanide baths which pose degradation problems for reverse osmosis membranes and ion exchange resins. Another 6% of Cd plating is done on lines employing evaporative recovery on the post-plating rinse. Thus, for the simulation, a total of 10% of the Cd plating involves the use of some form of recovery measure. An estimated 40% of Cd plating lines discharge to chemical destruct waste treatment systems, and 50% of Cd plating waste is released untreated either to sewer collection networks or to natural waters (10, 14).

Studies suggest that 90% of the electroplating industry discharges to sewage treatment plants, and

10% discharge directly to natural waters (7, 14). Chemical destruct waste treatment system metal removal efficiencies vary widely from less than 50% to almost 95% as a function of a wide variety of variables including treatment system configuration as well as maintenance and operating procedures (8). For the purpose of the present calculation, it is assumed that chemical destruct system metal removal efficiences average 90%, with the balance being discharged in the plant waste stream. For shops employing chemical destruct waste treatment and discharging to sewers, metallic sludges removed as clarifier underflow are given to scavengers. It has further been observed that direct dischargers dispose of clarifier sludge at largely unlicensed sites, typically on company owned land (8).

As previously indicated, 90% of the Cd purchased by the plating industry is actually plated on work pieces (14). Inasmuch as at present there is insufficient data to determine sources of Cd in steelmaking scrap originating from the use of Cd-bearing alloys, etc., it has been assumed for the present calculation that all Cd found in such scrap originates with a plated workpiece. With this assumption, 13% of plated Cd is processed through steel refining furnaces. The other 87% is land-disposed.

Cadmium Pigment Production

The major sources of Cd discharge to the environment from a Cd pigment facility are quench water discharges from the quench tank and from the filter press. Where waste treatment is practiced, these streams are fed to Cd salvage clarifiers where pH is adjusted and Cd, in the precipitated/suspended solids form, is allowed to settle. Clarifier sludge is sold to salvage plants who reclaim the Cd metal. A Cd flow survey was made by Purdue at one of the five plants. Results of the survey indicate that 6.8% of the Cd purchased for pigment manufacture is lost to aqueous waste streams. The salvage clarifier in the plant surveyed by Purdue was 70% efficient in removing Cd from the input raw waste stream. Thus 2% of the Cd purchased for the plant is discharged in the plant waste stream. Pending receipt of further data, the plant surveyed above will be used to represent the Cd pigment industry. In the present calculation 80% of aqueous waste generated by the industry is treated by pH adjustment and clarification, and 20% of the waste is discharged from plant sites untreated. It is further estimated that 70% of the products employing Cd pigments are landfilled, and 30% input to municipal or commercial incinerators. All Cd pigment waste is assumed to be discharged to sewer systems.

Cadmium Plastic Stabilizers

The production process for Cd stabilizers involves dissolving the metal oxides in acids. For liquid stabilizers the resulting solution is filtered and the residue is disposed of to landfill. For the present calculations 2% of the Cd used in the production of liquid stabilizers is lost to filter residue. In the production of solid stabilizers Cd salt is precipitated out of solution. The precipitation/settling is estimated to be 96% efficient for the production of Cd stearates and laurates, with the remaining Cd (4%) leaving the process as an aqueous waste. These estimates are subject to revision as more data become available.

In the present simulation, 50% of the waste water generated in the solid stabilizer production process is assumed to be treated. It is estimated that on an industry-wide basis 25% of Cd dry stabilizer aqueous waste is treated, and 75% is discharged untreated. As with Cd pigment product disposal, disposal of 70% of the Cd stabilized plastic products is landfill and 30% by way of municipal or commercial incinerators.

Nickel-Cadmium Battery Production

There are two types of Ni-Cd batteries produced in the U. S., the pocket plate cell and the sintered plate cell. Cd is used in the manufacture of the negative plate. The manufacturing processes, and thus the environmental implications, of the two types of plates are substantially different.

Pocket Plate Cell. Electrolytically active material for the pocket plates is prepared either by mixing powdered Cd or Cd compounds with an expander, or by the electrolytic coprecipitation of Cd and iron from an acid electrolyte. The major mechanism for Cd loss in this process is the generation of Cd-rich dust which winds up disposed of as a solid waste (~90%), or washed into flow drains (~10%) and thereby into the plant aqueous waste stream. For the purpose of the present calculations, 3% of the Cd purchased by the industry for pocket cell batteries winds up as dust losses. Floor drain runoff is typically not submitted to waste treatment.

Sintered Plate Cell. Plate-type cells are commonly made by the deposition of CdO on a porous nickel plaque or screen by electrodeposition from a solution of a soluble Cd salt or by soaking in a Cd nitrate solution. The negative electrodes are then put through several charge-discharge cycles and subsequently washed. The wash water and the electrolytic solution used in the charge-discharge cycles are discarded. Cd losses in these steps average 5% of the Cd purchased by the industry for

sintered plate cell production.

The fate of aqueous waste discharged from Ni-Cd battery plants is for the present calculations equally divided between natural waters and sewer collection systems. For the present simulation, on a nationwide basis, plants engage in waste treatment (pH adjustment, precipitation and settling) for the control of Cd in 50% of plant discharge. Cd removal efficiencies are similar to those achieved by chemical destruct technology in the electroplating industry (90%). It is further estimated that at present 10% of the Cd consumed by the industry is reclaimed. The other 90% is ultimately disposed of to land. At present 70% of the Ni-Cd batteries produced in the U. S. are of the sintered plate type, and 30% are of the pocket plate variety.

Recycling of Cd-Plated Steel Scrap

The recycling of #2 dealer bundle scrap through steel refining furnaces represents the primary mechanism for the release of Cd from steelmaking facilities. The three types of refining furnaces presently in use in the steel industry are the basic oxygen, electric arc, and open hearth. Work performed by the Purdue group at a large midwestern steel mill provides much of the data base for the COMP model formulation (24–30). Cd concentrations in steelmaking dust for the three types of furnaces are given in Table 2 (24).

Table 2. Cd concentrations in steelmaking dust.

Process	Dust, lb/ton steel produced	Cd concn in dust, ppm
Open hearth	10	250
Basic oxygen	30	80
Electric arc	20	580

On taking a baseline annual production rate of 150,000,000 tons, and assuming that 62.5%, 15%, and 22.5% of this amount is produced, respectively, by the basic oxygen furnace, open hearth, and electric arc processes, then a total of 309 Mt Cd/yr appears presently in steelmaking dust. It follows that 33% of the Cd input to U. S. steel refining furnaces is processed through basic oxygen units, 8% through open hearths and 59% through electric arc furnaces. If it is assumed that 90% of the Cd input to the furnace is found in the dust (the rest being in furnace underflow/slag and as a trace impurity in the product steel), then there is a total annual input of 343 Mt of Cd to the nation's steel refining furnaces.

In the present calculation it is assumed that particulate emissions from open hearth furnaces are controlled by electrostatic precipitators, basic oxy-

gen furnace particulate by Venturi scrubbers, and electric arc furnace particulate emissions are controlled by baghouses. Particulate emission control efficiencies for the wet scrubber, electrostatic precipitator and baghouse units under typical operating conditions are derived from measurements performed by the Purdue group (24) supplemented by data available from industry (J. R. Brough, private communication). These efficiencies are estimated to be 90, 92.3, and 95% for the scrubbers, precipitators, and baghouses, respectively. Fractions of Cd-bearing aqueous waste discharged to natural waters and sewer collection systems, are derived from an analysis of the fate of aqueous discharges from steelmaking facilities in northwest Indiana.

The fate of Cd released to the atmosphere from steel refining furnaces, i.e., rural soil, urban sewered areas, urban unsewered areas, and urban soils were determined by calculating Cd dispersion from steelmaking facilities in the Chicago-Gary-East Chicago area using the ATM Gaussian plume model. A map of the area is given in Figure 3, and results of the calculation are shown in Figure 4.

Coal-Fired Power Plants

While coal is commonly used in many industries, the main use of coal in the United States is for the generation of electricity. In 1978 consumption of all types of coal for the generation of electricity was some 3.51×10^{11} kg (31). The average cadmium content of coal commonly used in the U. S. is 0.21 μg/g (32). This value is within the range discussed
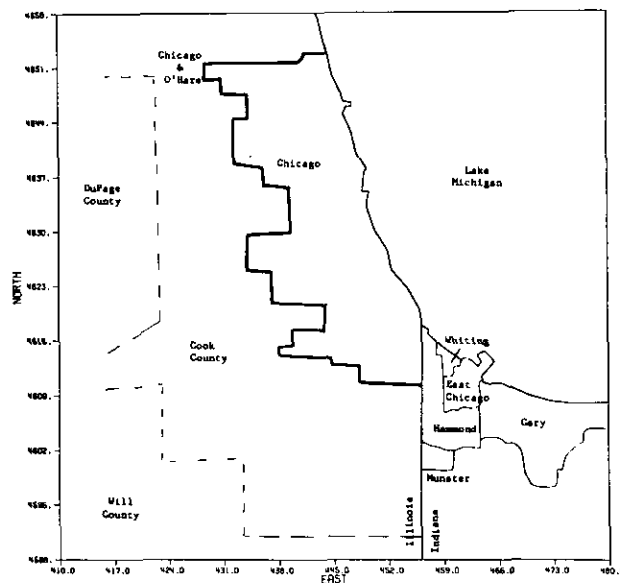

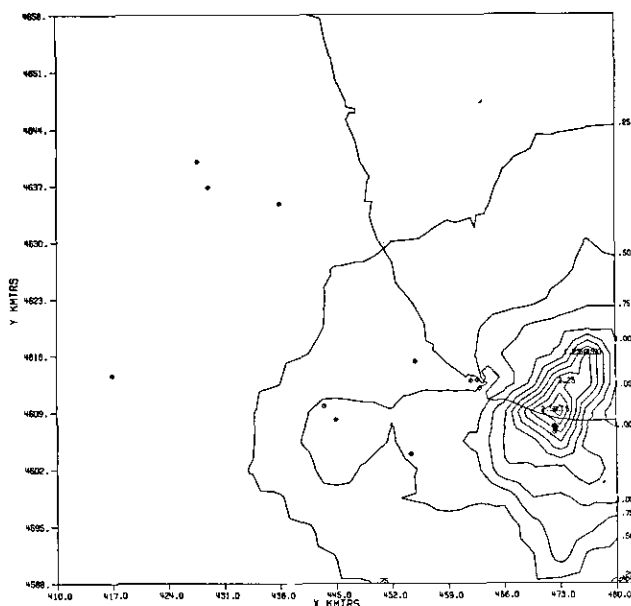Figure 3. Chicago-Northwest Indiana prototype/study area.

FIGURE 4. ATM results for suspended Cd from steel production (ng/m³) in the Chicago-Northwest Indiana area.

by Klein et al. (33) and appears realistic. This indicates that 7.37 × 10⁴ kg cadmium passes through coal-fired power generating plants annually.

The consumption of coal by power plants results in the production of bottom slag and fly ash. Approximately 8.9% of coal is ash (34), which represents the bottom slag and ash flow output of the plant. Of the 8.9%, 57% is bottom slag produced from the combustion of coal, and the remaining portion of the 8.9% is fly ash which enters the stack gas stream. Of coal-fired power plants in the U. S., 2% are assumed to be scrubber-controlled in addition to being precipitator-controlled. Scrubbers are assumed to be 90% efficient at removing cadmium from inlet gas, the remaining 10½ is passed on to precipitators for additional control. Precipitators receive some 6.88 × 10⁴ kg Cd/year, removing 90% (6.20 × 10⁴ kg Cd/yr) to the slag. The ash stockpile receives furnace residue and collected fly ash, 20% of which is used in cement and asphalt production. The remaining 80% is deposited in landfills.

The discharge of Cd to the atmosphere as a component of power plant stack gas particulate gives rise to a consequent deposition/fall out of Cd-bearing particulate on both urban and rural areas. Rural soils are considered to be sinks for Cd. Urban systems on the other hand are commonly served by a sewer system of some type. Cd deposited on urban sewered areas is susceptible to wash-off into combined sanitary/storm sewer systems. Although only 2% of the U. S. is urban (35), it is estimated that 50% of the U. S. coal-fired generating capacity

is located in the urban environment.

It is further assumed that, of the 50% of Cd deposited in an urban environment, 40% falls on areas served by sewers, and 60% upon unsewered urban areas. Of the urban areas served by sewers systems, 73% have separate sanitary and storm sewers, 27% have combined sewer systems (36).

Sewage Treatment Plant

A sewage treatment plant Cd flow model is currently under development which incorporates various system components associated with primary, secondary and tertiary treatment. Data for this model are being derived from a study of Cd flow in the Kokomo, Indiana treatment plant and collection network being conducted by Purdue for EPA's Municipal Environmental Research Laboratory in Cincinnati. Other studies have been performed which will be of use, including that done on the Anderson, Indiana plant (37).

Pending development of the foregoing model, present calculations of Cd flow associated with sewage treatment plant operations have been performed with a vastly simplified representation involving a two-way branching of Cd entering a plant between "pass through" (in plant effluent) and removal in digestor sludge. A study of the relative fractions of Cd that are diverted to digestor sludge or passed through the plant was conducted by the Purdue group on nine treatment plants located in Indiana (24, 38). On the basis of the data collected in this study, the Cd is split in the present calculation as 68% in digestor sludge and 32% in "pass through."

Estimates of the relative fractions of municipal sewage sludge which are landfilled (32.4%), applied to commercial cropland (27.5%), applied to home garden soil (5%), and incinerated (35%) were derived from a survey by Purdue of these practices in Indiana and from the literature (24, 39-41).

Municipal Incinerator

Cd is released from municipal incinerators as a result of the vaporization of the metal contained in such materials as Cd stabilized plastics and Cd pigmented combustible products found in domestic and commercial solid waste.

Much of the data regarding Cd flow in such a facility is derived from an intensive mass flow balance for Cd performed by the Purdue group on the Nicosia municipal incinerator in East Chicago, Indiana (27, 42). The primary Cd streams from such a facility are furnace underflow/residue, stack gas emissions, and clarifier output from wet scrubber

controlled facilities. The fate upon deposition of Cd emitted to the atmosphere from an incinerator facility was determined by calculating particulate dispersion from the Nicosia incinerator and its subsequent deposition pattern with the ATM model.

For the purposes of the present calculation, it is assumed that atmospheric emission control devices for municipal incinerators are divided evenly between wet scrubbers and electrostatic precipitators. Cd removal efficiencies for wet scrubbers are estimated to average out to 90% for incinerators, and precipitator Cd removal efficiencies are presumed to be 94%. These figures are substantially lower than those advertised for these units. Part of the reason for these relatively low efficiencies is that Cd tends to segregate toward the submicron particle size fraction, which is more difficult to trap in stack gas collection devices than are the larger particle size fractions.

Scrubber clarifier Cd removal efficiencies are estimated to average 94% on a industry-wide basis. Clarifier effluent is assumed to be discharged equally between natural waters and sewage treatment collection systems. Of the Cd input to the furnace, 90% is estimated to be vaporized and escape to stack gas, 10% is assumed to remain in the furnace residue and is removed in firing chamber underflow. Of the Cd runoff into combined storm-sanitary sewer systems, 27% is estimated to be input to sewage treatment systems, and 73% is discharged to natural waters.

Ten-Year Simulation Results

The cumulative amounts of Cd consumed by the major users of the metal are given in Table 3 for the simulation period. Also given are annual consumption figures at the conclusion of the period. Cadmium flow to the primary environmental receptors as well as waste processing facilities are specified on a national basis for the sources specified below.

Table 3. Cd consumption for ten-year simulation period assuming present use pattern persists.

Use	Total consumption × 10^{-3}, Mt	Annual consumption rate at end of simulation period × 10^{-3}, Mt
Electroplating	33	4.1
Pigments	7.2	0.90
Plastics	12	1.49
Ni-Cd Batteries	3.0	0.37
Miscellaneous	4.8	0.60

Table 4. Electroplating and plated product disposal Cd flow analysis for ten-year simulation period.

Fate	Flow, Mt
Land disposal	1067
Land filling	26400
Natural waters	203
Recovery	80
Sewage treatment	1580
Steel scrap recycle	3620

Electroplating and Plated Product Disposal

Over the ten-year simulation period, 33,000 Mt of Cd will be consumed by the electroplating industry. Of this amount, 29,700 Mt will be deposited on workpieces and 3300 Mt will be lost to waste water, spills and concentrated waste. Given the present day level of recovery efforts, only 80 Mt (2.2%) of this amount will be recovered for reuse in plating operations. Of the amount recovered, 16 Mt will be recovered by ion exchange units, 16 Mt by reverse osmosis, and 48 Mt by way of evaporative recovery. Another 1430 Mt will be subjected to chemical destruct waste treatment, and 1790 Mt will be discharged untreated from plating facilities. This will in turn generate 1310 Mt of clarifier underflow sludge, 1180 Mt of which will be hauled away by scavengers/waste processors, and 130 Mt disposed of in unauthorized sludge pits located primarily on land owned by shops discharging directly to natural waters. Finally, 1580 Mt of Cd will be discharged to sewage treatment collection systems, and 203 Mt will be discharged directly to natural waters.

Of the 29,700 Mt of Cd deposited on workpieces over the ten-year simulation period, 26,020 Mt are assumed to be disposed of to land at the end of the period of product usefulness, and 3,620 Mt are input to steel refining furnaces as part of the #2 dealer bundle scrap charge stream. These flows are summarized in Table 4.

Cadmium Pigment Production and Product Disposal

Table 5 portrays the flow of Cd associated with pigment production and subsequent product disposal.

Production losses of Cd to plant waste water during the simulation period are 490 Mt. Of this amount, 80% (392 Mt) receives some type of waste treatment/recovery measures, and 20% (98 Mt) is discharged from pigment production facilities without treatment. Sewage treatment plants are expected to receive 176 Mt of Cd from pigment production facilities over the ten year simulation

Table 5. Cd pigment production and disposal flow analysis for ten-year simulation period.

Fate	Flow, Mt
Incineration	1910
Landfill	5130
Sewage treatment	176

period. The disposal of Cd pigment products will result in a flow of 1910 Mt of Cd through municipal incinerators, and the depositing of 5130 Mt in land disposal sites.

Cd Plastic Stabilizers

The producers of Cd stabilizers are expected to consume 12,000 Mt of the metal over the course of the ten-year simulation period. Of the 6000 Mt of Cd consumed in the production of dry stabilizers, 4% or 240 Mt ends up as production losses. In the production of liquid stabilizers, there are no aqueous discharges, while 60 Mt of Cd is disposed of as a solid waste to landfill. U. S. sewage treatment plants are projected to receive 138 Mt of Cd from stabilizer producers during the ten year simulation period. Natural waters will receive 37 Mt of Cd, 8480 Mt of Cd will be disposed of to land in the form of solid waste, and 3340 Mt will flow into municipal incinerators in the form of combustible plastic products. This situation is summarized in Table 6.

Nickel-Cadmium Battery Production and Disposal

Ni-Cd battery producers consume 3000 Mt of Cd during the ten year simulation period. Of this amount, approximately 27 Mt will be lost as fugitive dust generated in the pocket plate cell production process. Approximately 1.35 Mt of this amount will be washed into floor drains and discharged untreated, another 1.35 Mt will be washed into drains and subjected to pH adjust/clarification waste treatment, and 24.3 Mt will be disposed of as solid waste (dust), primarily collected in baghouses designed to keep ambient air Cd levels in the working environment at tolerable levels. With respect to the sintered plate cell production process, 105 Mt of Cd

Table 6. Cd plasticizer production and product disposal flow analysis for ten-year simulation period.

Fate	Flow, Mt
Incineration	3340
Landfill	8480
Natural waters	37
Sewage treatment	138

is lost to plate wash water and spent charge-discharge cycle electrolytic solution. Of this amount 53 Mt is discharged untreated to natural waters, and 53 Mt is released to U. S. sewage treatment plants. In total, 2868 Mt of Cd will be actually used in battery units. 287 Mt of this amount will be recycled by way of spent battery reclaim, and 2581 Mt will be disposed of to land. Table 7 gives cumulative Cd flows to major receptors associated with current production and disposal practices.

Table 7. Ni-Cd battery production and disposal Cd flow analysis for ten-year simulation period.

Fate	Flow, Mt
Landfill	2610
Natural waters	53
Reclaim	287
Sewage treatment	53

Table 8. Miscellaneous use Cd flow analysis for ten-year simulation period.

Fate	Flow, Mt
Incineration	440
Land disposal	93
Landfill	3720
Natural waters	8
Recovery/reuse	35
Steel scrap recycle	310
Sewage treatment	165

Miscellaneous Cd Uses

As previously indicated, the environmental impact of Cd discharges from production facilities representing miscellaneous uses is presumed to be equivalent to the relative consumption weighted impacts of the four major uses. Table 8 summarizes the various cumulative flows generated by way of this weighting process.

Inadvertent Source Cadmium Flow Analysis

Table 9 gives cumulative Cd flows for the four inadvertent sources included in the ten-year flow simulation. Note that the three significant sources of Cd to the atmosphere have specified airborne particulate deposition areas including rural, urban sewered, and urban unsewered. Rural deposition carries with it a potential for cropsoil contamination, whereas deposition in sewered urban areas results in Cd washoff in precipitation events to sewer collection systems. This in turn will result in a mea-

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Table 9. Inadvertent source Cd flow analysis for ten-year simulation period.

Process	Fate	Flow, Mt[a]
Sewage treatment plant	Commercial crop soil	427
	Home gardens/lawns	78
	Incineration	543
	Landfill	504
	Natural waters	735
Refuse/sludge incineration	Atmosphere	404
	Rural area	141
	Urban sewered area	158
	Urban unsewered area	105
	Landfill	5595
	Natural waters	167
	Sewage treatment	95
Steel scrap recycle	Atmosphere	265
	Rural area	79
	Urban sewered area	121
	Urban unsewered area	63
	Landfill	3500
	Natural waters	102
	Sewage treatment	57
Coal-fired power plants	Atmosphere	76
	Rural area	38
	Urban sewered area	15
	Urban unsewered area	23
	Cement/asphalt products	147
	Landfill	591
	Natural waters	11.2
	Sewage treatment	2.4
	Slag/collected fly ash	738

[a] Multiple accounting for selected Cd streams.

sure of metal contamination of sewage sludge with an attendant impact on its landspreading potential.

Total Cd flow to U. S. sewage treatment plants in the ten year simulation period is 2287 Mt. Of this amount, 735 Mt is "passed through" to natural waters, and the balance (1552 Mt) is deposited in digestor sludge. Given the sludge disposal practices outlined in the above discussion, 504 Mt of Cd is deposited in sludge landfill operations, 427 Mt is applied to cropland via sludge landspreading practices, 78 Mt is applied by home gardeners to non-commercial cultivated plots, and 543 Mt is fed to sludge incinerators.

Over the course of the ten-year simulation period, approximately 6250 Mt of Cd flows through U. S. municipal incinerators as a consequence of the major Cd uses. Of this amount, 6.5% or 404 Mt is discharged to the atmosphere. Subsequent fallout of Cd discharged to the atmosphere results in the deposition of 141 Mt on rural soils, 158 Mt on urban sewered areas, and 105 Mt on urban non-sewered areas. Runoff from urban sewered areas results in the input of 30 Mt of Cd to municipal sewer systems. Natural waters receive 147 Mt of Cd as a

result of atmospheric fallout of metal discharged from municipal incinerators, as well as from the output of scrubber clarifiers serving wet scrubbing equipment on incinerator stacks. Urban soils (excluding runoff from paved areas) receive 113 Mt of Cd by way of atmospheric fallout. The flow of Cd to landfill operations attributable to firing chamber underflow, scrubber clarifier underflow and precipitator dust is 5180 Mt.

As indicated in the discussion of Cd flow in the electroplating waste treatment/recovery module, 3930 Mt of Cd will flow through steel refining furnaces in the ten-year simulation period as the result of the recycle of Cd plated material contained in #2 dealer bundle scrap. Of this amount, 1298 Mt flows through basic oxygen furnaces, 314 Mt through open hearth, and 2318 Mt through electric arc furnaces. The result is atmospheric discharges of 129 Mt, 23 Mt, and 115 Mt Cd from the three foregoing types of furnaces, respectively, during the ten-year simulation period. Some 195 Mt of Cd is carried off in the slag/furnace underflow streams from the three types of furnaces. Approximately 1100 Mt of Cd fume is trapped in water sprays used to control particulate emissions from basic oxygen furnaces. Of this amount, 1000 Mt is disposed of to landfill in the form of a scrubber water clarifier underflow, 57 Mt is discharged to natural waters from clarifier overflow, and another 57 Mt is directed to U. S. sewage treatment plants by the same mechanism. In the open hearth process, 280 Mt of Cd is disposed of to land in the form of electrostatic precipitator dust, whereas 2020 Mt of Cd is disposed of to land in the form of electric arc furnace baghouse dust.

Cd contained in furnace underflow and collected fly ash destined for landfill and paving material from coal-fired power plants over the ten year simulation periods totals 591 Mt. Another 147 Mt of this material is utilized for cement and asphalt products. The Cd input to U. S. sewage treatment plants attributable to power plant operations in only 2.4 Mt. Discharge to natural waters totals 11.2 Mt. Rural soils receive 38 Mt of Cd by way of aerial deposition of Cd-bearing particulate from power plant stacks, while urban areas (including sewered and unsewered) receive a total of 38 Mt.

Conclusions

The foregoing simulation of Cd flow associated with major uses and selected inadvertent sources enables one to estimate, on an aggregate/national basis, the relative magnitudes of their discharges to major environmental and waste processing receptors. Table 10 summarizes these discharges on a comparative basis. Note that refuse/sludge inciner-

Table 10. Comparative Cd flow analysis for ten-year simulation period.

Process	Cd flow, Mt/10 yr			
	Atmosphere	Landfill	Natural waters	Sewage treatment
Electroplating	—	27467	203	1580
Pigments	—	5130	—	176
Plastics	—	8480	37	138
Ni-Cd batteries	—	2610	53	53
Miscellaneous uses	—	3720	8	165
Steel scrap recycle	265	3500	102	57
Coal-fired power plants	76	591	11	2.4
Refuse/sludge incineration	404	5595	167	95
Sewage treatment	—	1010ᵃ	735	—
Totals	745	58103	1316	2266

ᵃ Includes all land disposed sludge.

ation represents the heaviest source of Cd to the atmosphere followed by steel refining furnaces processing #2 dealer bundle scrap. This ranking of atmospheric sources is likely to change when lead and zinc refineries are factored into the simulation.

Inasmuch as the electroplating industry represents by far the largest consumer of Cd in the U. S. (55%), it is not surprising that a large share of the use-related Cd movement in the U. S. environment is attributable to this industry. Of the sources considered in the present simulation, it accounts for 70% of the Cd discharge to sewer collection systems, 47% of the Cd disposed of to land, and 15% of the Cd discharged directly to natural waters. If one factors in the 70% contribution to sewage plant discharges, then 55% of Cd discharges to natural waters are directly or indirectly attributable to the electroplating industry. In a similar fashion, the industry is directly or indirectly responsible for 48% of the Cd disposed of the land, and by way of the recycle of Cd plated steel scrap and sewage incineration, accounts for approximately 40% of the Cd discharged to the atmosphere.

The Cd pigment industry accounts for only 7.8% of the total Cd discharged to sewage treatment plants and, by way of the parameters underlying the present simulation, does not discharge directly to natural waters. The indirect Cd discharge to natural waters through sewage treatment plants accounts for approximately 4% of the U. S. total. The landfilling of production waste and pigment products makes up 8.8% of the total Cd disposed of the land in the U. S., while the incineration of pigment products generates 18% of the Cd discharged to the atmosphere. A similar analysis of the Cd plasticizer industry indicates that it is responsible for 2.8% of the Cd discharged to U. S. waters, 14.6% of land-disposed Cd, and 31% of the Cd emissions to the atmosphere.

The Ni-Cd battery industry represents the small-

est of the four major Cd users, accounting for only 5% of Cd sales in the present simulation. The industry is responsible directly and indirectly (through sewage treatment plants) for 8% of Cd discharged to natural waters, and 4.5% of the Cd land disposed in the U. S. It should be pointed out that the environmental impact of the recycling of Ni-Cd batteries was not included in this simulation due to a lack of data in this area at the time of preparation of this paper. Miscellaneous Cd uses, as indicated previously, are assumed to have an environmental impact equivalent to the consumption weighted impacts of the specific uses.

The four non-use-related Cd sources considered in the present simulation account for all of the Cd input to the atmosphere, 18% of the Cd disposed of to land and, primarily due to the presumed 30% Cd pass-through by sewage treatment plants, 77% of the Cd discharged to natural waters. Somewhat surprising is the relatively small contribution of coal-fired power plants to Cd discharge to the environment.

In conclusion, it appears that regulation of the Cd electroplating industry represents the maximum payoff strategy for the reduction of Cd flow in the U. S. environment. This is true simply because of the large amount of Cd consumed by this industry. Clearly, as long as sewage sludge continues to be contaminated by Cd to the degree it presently is, its spreading on cropland represents the primary mechanism of exposure to Cd for the general population. Municipal waste management strategies designed to minimize sludge landspreading, however, typically involve environmental trade-offs. In particular, a policy decision to force incineration of all municipal sludges, as opposed to landspreading and/or landfilling, would increase Cd discharges to the atmosphere by 15% while eliminating human exposure to Cd by way of crop uptake from sludge-contaminated soils. The primary factors involved in

weighing the relative advantages of such trade-off strategies are health related, e.g., one must consider the relative toxicity of respired Cd as opposed to that ingested in the diet.

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